DOT/FAA/AM-92/22

Office of Aviation Medicine
Washington, D.C. 20591

# Comparisons of Molecular Sieve Oxygen Concentrators for Potential Medical Use Aboard Commercial Aircraft

Harvey M. England, Jr.
Bruce C. Wilcox, Jr.
Garnet A. McLean

Civil Aeromedical Institute
Federal Aviation Administration
Oklahoma City, Oklahoma 73125

June 1992

Final Report







U.S. Department
of Transportation
**Federal Aviation Administration**

# NOTICE

Technical Report Documentation Page

| 1. Report No. | 2. Government Accession No. | 3. Recipient's Catalog No. |
|---|---|---|
| DOT/FAA/AM-92/22 | | |

| 4. Title and Subtitle | 5. Report Date |
|---|---|
| Comparisons of Molecular Sieve Oxygen Concentrators For Potential Medical Use Aboard Commericial Aircraft | June 1992 |
| | 6. Performing Organization Code |
| 7. Author(s) | 8. Performing Organization Report No. |
| H.M. England, Jr., B.C. Wilcox, Jr., G.A. McLean | |
| 9. Performing Organization Name and Address | 10. Work Unit No. (TRAIS) |
| FAA Civil Aeromedical Institute<br>P. O. Box 25082<br>Oklahoma City, OK 73125 | 11. Contract or Grant No. |
| | 13. Type of Report and Period Covered |
| 12. Sponsoring Agency Name and Address<br>Office of Aviation Medicine<br>Federal Aviation Medicine<br>800 Independence Avenue, S.W.<br>Washington, D.C. 20591 | 14. Sponsoring Agency Code |

15. Supplementary Notes

16. Abstract

Medically-impaired air travelers requiring supplemental oxygen must depend on airlines to provide oxygen cylinders. Performance, space, and cost are considerations in providing this service. Tests were conducted in an altitude chamber to assess the viability of Molecular Sieve Oxygen Concentrators (MSOC) as an alternative. Five different MSOC were placed in the altitude chamber, and connected to a mass spectrometer outside. Gas concentration was digitized at one sample-per-second and stored on line via a microcomputer. Tests at ground level showed four of the five MSOC produced oxygen at 95% purity at 2 liters per minute flow, which was maintained until 13,000 feet. Increasing altitude resulted in graded reductions of oxygen levels. At 25,000 feet, only two MSOC withstood sudden decompression. Results of this study indicate that some MSOC indeed have the potential to provide oxygen for the medically-impaired air traveler.

| 17. Key Words | 18. Distribution Statement |
|---|---|
| Molecular Sieve, Oxygen, Concentrators, Zeolites | Document is available to the public through the National Technical Information Service Springfield, Virginia 22161 |

| 19. Security Classif. (of this report) | 20. Security Classif. (of this page) | 21. No. of Pages | 22. Price |
|---|---|---|---|
| Unclassified | Unclassified | 10 | |

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

# COMPARISONS OF MOLECULAR SIEVE OXYGEN CONCENTRATORS FOR POTENTIAL MEDICAL USE ABOARD COMMERCIAL AIRCRAFT

## INTRODUCTION

At sea level the barometric pressure is 760 mm Hg, and the partial pressure of oxygen is 159 mm Hg. In a healthy person, this produces an arterial oxygen level of about 95 mm Hg, which results in an arterial oxygen saturation ($SaO_2$) of 97%. At a typical cabin altitude of 8,000 feet above sea level (ASL), the barometric pressure is 565 mm Hg and the partial pressure of oxygen is 118 mm Hg (1). This causes the arterial oxygen level to drop to as low as 65 mm Hg, resulting in a decrease of $SaO_2$ to around 89%. In air travelers with cardiopulmonary disease, arterial blood oxygen can fall to 40 mm Hg or lower, depending on the severity of impairment. Thus, despite the maintenance of a generally acceptable pressure gradient between the cabin and the outside atmosphere, the reduced ambient air pressure during commercial flight makes it necessary to provide supplemental oxygen to air travelers with significant pulmonary and/or cardiac impairment (2). Therefore, impaired persons who desire to travel by air should have an assessment of their medical condition prior to flight. Certain factors must be ascertained by a physical examination (3), which should include a pulmonary function study to determine if the impaired person has:

1). A Vital capacity greater than 50% of predicted ;

2). The ventilatory pattern is regular and consistent with a respiratory rate below 25 breaths per minute;

3). The resting PaO2 indicates that a minimal in-flight PaO2 will be 50 mm Hg or higher.

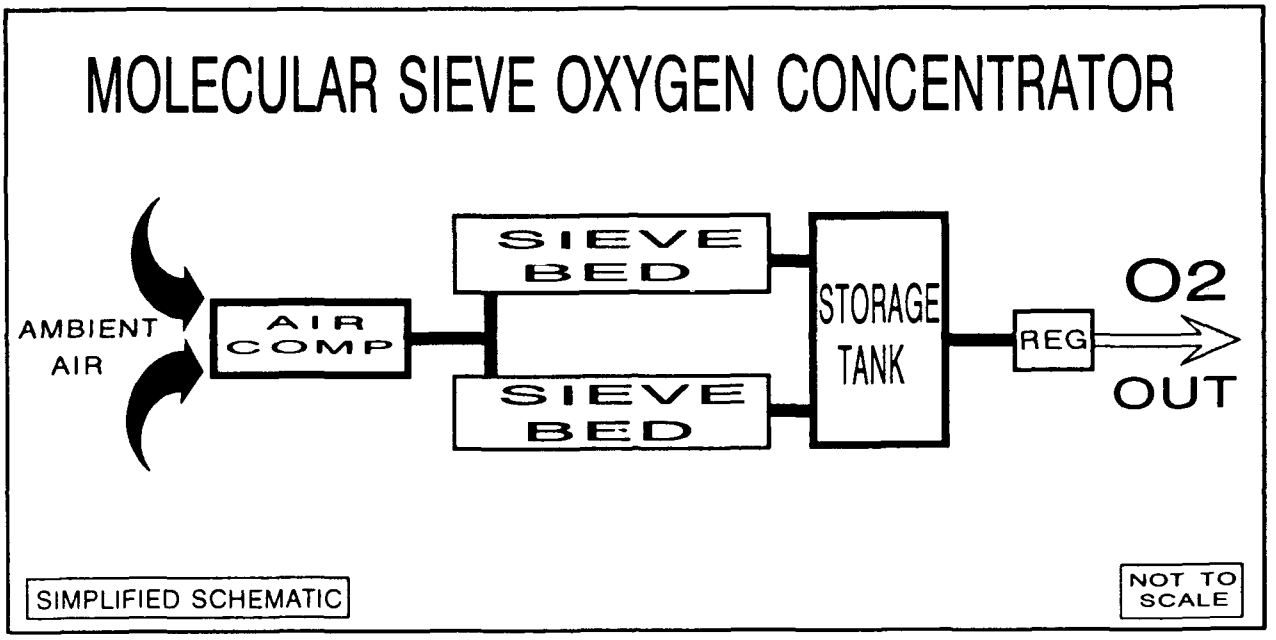
Currently, the physician makes a recommendation on whether the patient's medical condition will allow flight aboard a commercial aircraft. However, airlines may enforce other guidelines, as no regulations define criteria for accepting passengers aboard commercial aircraft.

At present, medically impaired air travelers are supplied supplemental oxygen via high pressure oxygen cylinders (2200 pounds per square inch, gage (psiG), provided by the airlines, after arrangements with an approved medical gas vendor have been made by the passenger. In the event that the flight connects with another, the passenger must make arrangements with another vendor in the connecting city to supply oxygen for the next flight. At best, this creates a cumbersome and expensive situation. The transportation and utilization of high-pressure oxygen cylinders are potentially hazardous. Thus, a literature search was conducted to investigate the potential for use of Molecular Sieve Oxygen Concentrators (MSOC) to provide supplemental medical oxygen aboard commercial aircraft.

Commercially available MSOC provide oxygen at concentrations of up to 95 percent, using internal pressures as low as 10 psiG. MSOC units function by concentrating the available oxygen in the ambient air. They utilize the pressure-swing method in which air is forced into containers filled with crystalline aluminosilicate compounds called Zeolites, the molecular sieve material. Zeolites are porous substances that occur naturally or may be produced synthetically. By varying the amount of alkali metals in the Zeolite crystals to obtain a certain molecular configuration, nitrogen from the air is specifically absorbed, allowing oxygen and argon to pass through preferentially. This action produces a concentrated, nearly oxygen-pure gas emanating from the MSOC. The flow of oxygen ranges from one-fourth liter per minute (L/min) to 5 L/min, and is usually delivered to medical patients through a nasal cannula attached to the MSOC by flexible tubing. The cannula consists of 2 pliable plastic prongs about one-half inch in length which are inserted into the nares. It is held in place by looping the tubing over the ears, or by placing an elastic strap around the head. Many cannula are also fitted with a reservoir that allows a lower, more consistent flow rate.

The performance of MSOC technology has been evaluated in military jet aircraft at high altitudes, using MSOC units that have been designed to provide all the oxygen required for the pilot and crew. These units are generally driven by bleed air ducted from the jet engines. Because the use of MSOC aboard commercial aircraft would be intermittent, using engine bleed air would be unsuited for medically-related oxygen needs. Thus, an alternate source of pressurized air would be needed for an MSOC unit to operate. This function is provided in currently available commercial MSOC by small air compressors, which are generally driven electrically by alternating current (AC) power, or in at least 1 commercial MSOC unit, direct current (DC) power. Use of electrically-powered air compressors makes such units potentially viable as an oxygen source for the air traveler requiring supplemental oxygen, although the reduction in the density of air at typical cabin altitudes of 8,000 feet ASL requires MSOC testing to assure adequate oxygen outflow. Figure 1 provides a generic block diagram of a commercial MSOC unit.

**Figure 1**




After obtaining the available information on MSOC technology, which consists of the basic theoretical details and military applications, but not commercial product data, we requested several major MSOC suppliers to provide demonstration units; however, we have not had the opportunity to test all MSOC units that are available. These units were tested in the Civil Aeromedical Institute (CAMI) altitude chamber to determine: (1) the performance of each unit at altitudes up to 25,000 feet ASL, (2) the effects on MSOC performance of a sudden decompression, and (3) the maximum oxygen level each unit would produce at 10 minutes after start-up at a simulated cabin altitude of 8,000 feet ASL. The following AC-powered units were tested: Forlife by AirSep, Puritan Bennett Companion 590, Mobiliare V by Invacare, and the DeVilbiss DeVo MC-44; the (portable) 12-volt DC-powered Roman Labs Freedom $O_2$ DC-100 was also tested.

## METHODS

The MSOC units were adjusted to an approximate flow-rate of 2 L/min , ambient temperature pressure dry (ATPD) and placed in the CAMI altitude chamber. Each MSOC gas outlet was then connected to a 3-foot section of Tygon tubing, which incorporated a sampling tube from a Perkin-Elmer MGA-1100 medical gas analyzer. The sampling tubes were passed through the altitude chamber wall to the analyzer located outside in the control booth. Analog electronic gas concentration data were digitized at 1 sample-per-second and stored on-line via microcomputer.

**TEST 1.** This test was designed to determine the performance characteristics of MSOC units at altitudes up to 25,000 feet ASL. In this test the altitude chamber door was closed and, after a 20-minute equilibration period, data collection began at ground level (1,300 feet ASL). The oxygen output from each MSOC unit was recorded for 1 minute, before raising the altitude in the chamber by 1,000 feet, where another recording was accomplished. This sequence was repeated at 1,000-foot intervals until an altitude of 25,000 feet ASL was reached. After the data were collected at this altitude, the test was stopped and the chamber returned to ground level.

**TEST 2.** The second test occurred on a day subsequent to the first test and was designed to answer 2 questions: (1) Does the measurement time "step function" used in Test 1 provide an overestimation of oxygen purity at increasing altitudes because of residual oxygen held in the MSOC unit storage tanks, and (2) What would be the effects of a sudden decompression on MSOC function? This test also began at ground level; however, immediately after the MSOC units were actuated, the altitude chamber door was closed and a maximum-rate (10,000 ft/min) ascent to 30,000 feet ASL was

executed. The ascent required 5 minutes to accomplish, and the 30,000-foot ASL altitude was maintained for 5 minutes before descending to 25,000 feet ASL, where data collection began. Data were collected in a manner analogous to Test 1, except for the descending altitude profile.

**Test 3.** The third test was conducted to determine the MSOC performance at the 8,000 feet ASL simulated cabin altitude. In this test the MSOC units were initially turned off while the altitude chamber was raised to 8,000 feet ASL, after which each unit was individually started and its output measured continuously for 10 minutes. The intent was to determine if a second MSOC unit could be used as a relatively immediate back-up if 1 MSOC unit failed inflight and needed to be replaced by another.

## RESULTS

In initial testing at ground level, all the MSOC units were able to produce oxygen at concentrations above 90% at a 2 L/min flow (recorded visually). The time required for each unit to achieve this level was variable. During the tests, the AC-powered MSOC units achieved both higher concentrations and faster concentration rise-times than did the DC-powered Freedom $O_2$ DC-100. (Note that flow from the DC-100 could not be determined as the unit had no flow meter.)

**Test 1.** The Forlife, Companion 590, Devo MC-44, and Mobilaire V units maintained oxygen purities of at least 95% until the chamber reached 13,000 feet ASL. Above that altitude only the Forlife and Companion 590 units maintained 94% oxygen purity for the duration of the test; the oxygen levels fell continuously from the other units. The Forlife and Companion 590 units were also the only ones to maintain the 2 L/min. Increases in altitude reduced flow from the other units in a gradual manner.

At 13,000 feet ASL, the Devo MC-44 and Mobilaire V units provided only 94% oxygen. At 15,000 feet ASL the Mobilaire V unit was producing 90% oxygen and the Devo MC-44 unit output was 86%; oxygen concentrations had fallen to 71% and 75%, respectively, at 20,000 feet ASL. These values were little-changed at the maximum altitude of 25,000 feet ASL.

The Freedom O2 DC-100 was observed to reach an oxygen purity of only 87% at ground level during this test, but purity increased to a maximum level of 92% at 6,000 feet ASL. Perhaps this increase with altitude reflected the need for a longer warm-up period to attain maximum operating effectiveness. However, given the ability of this unit to achieve a higher oxygen concentration in less time in earlier ground-level tests, an intermittent equipment problem may also have been responsible. At 15,000 feet ASL, the DC-100 produced an oxygen purity of 65%, and at 20,000 feet it fell to a 40% concentration. Figure 2 shows the performance of all the MSOC units during Test 1.

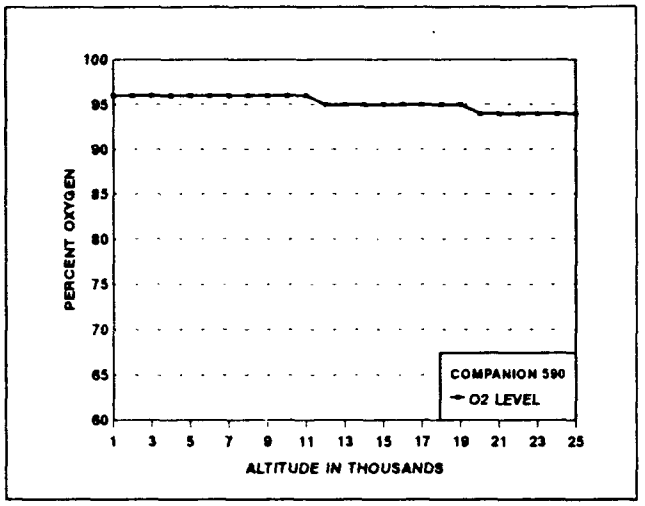
**Test 2.** After the maximum-rate ascent to 30,000 feet ASL, followed by the 5-minute wait, the chamber altitude was lowered to 25,000 feet ASL to begin data collection at 1,000 feet decrements. All the units performed less effectively than at ground level or during the ascent profile used in Test 1. The Forlife and Companion 590 units were actually the only units to achieve O2 concentrations above 90%. Note that the Forlife and Companion 590 units were observed at 25,000 feet ASL to have an oxygen flow of only 1.5 L/Min which returned to 2 L/Min at 15,000 feet ASL and below.

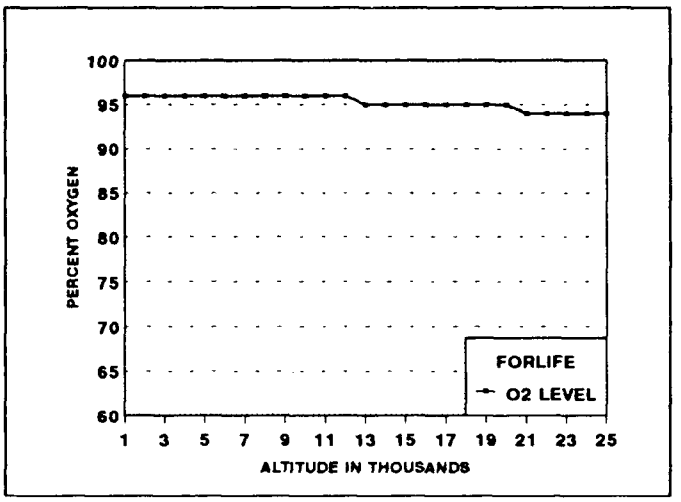
In contrast, none of the other MSOC were observed to register any oxygen flow during the test. Despite this fact, the Mobilaire V unit was observed to register small, variable oxygen percentages above ambient during the test. This suggests that either a small amount of residual concentrated oxygen was still being released from the sieve bed, or the unit was functioning at minimal efficiency. The increase to a 27% oxygen level upon reaching ground level favors the latter interpretation. This was not the case for the Devo MC-44 and DC-100, as neither unit appeared to operate at all.

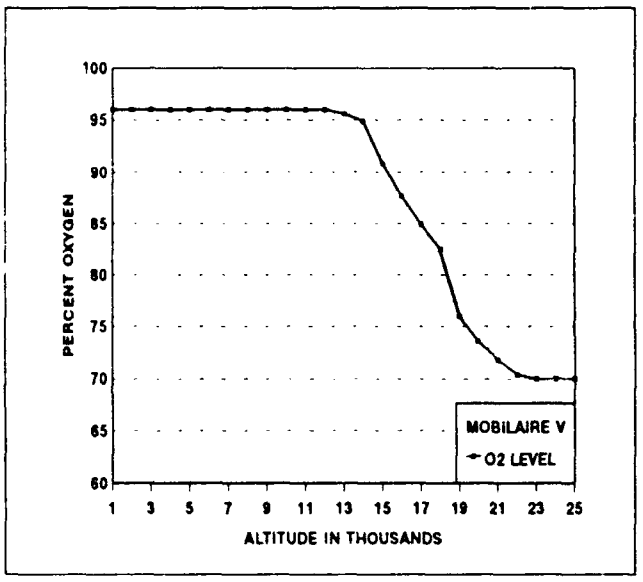
All the MSOC units have a low pressure switch with auditory alarm. Three of the units were designed to shut down should the air pressure fall too low. Auditory alarms were heard during the test from outside the chamber. Figure 3 shows the performance of all MSOC units during the test.

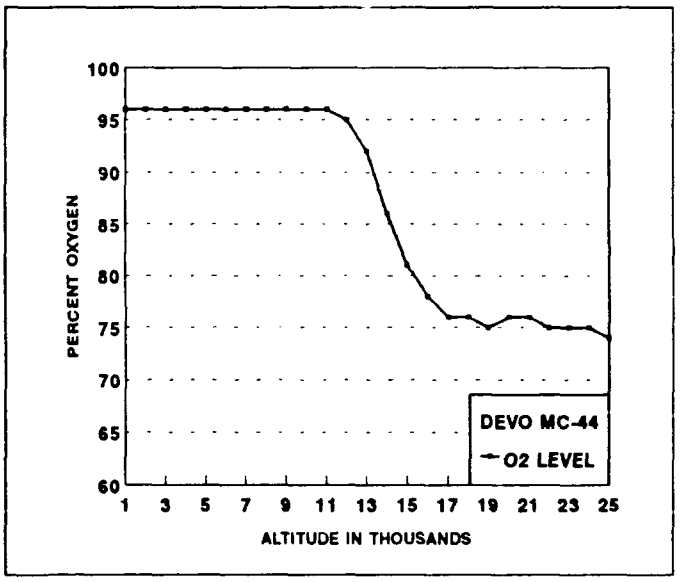
**Test 3.** During the third test at 8,000 feet ASL, all units performed in a manner similar to that at ground level. In increasing order of oxygen concentration rise-time for AC-powered units, the Mobilaire V stabilized at maximum oxygen levels after at 7.5 minutes, the Companion 590 achieved maximum performance at 8 minutes, the Forlife reached maximum oxygen concentration at 8.5 minutes, and the Devo MC-44 reached maximum performance at 10.5 minutes. With the exception of the Companion 590, the oxygen concentration rise-time curves were somewhat flatter at altitude than at ground level.

Figure 2. MSOC Tests From 25K ASL.



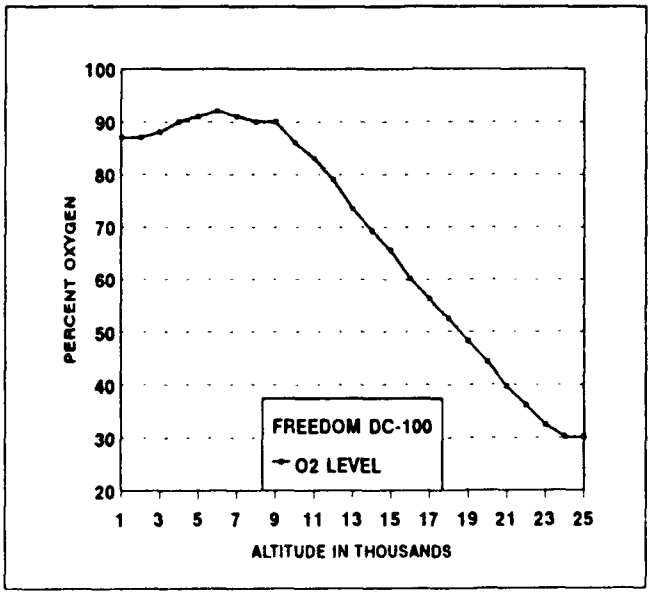
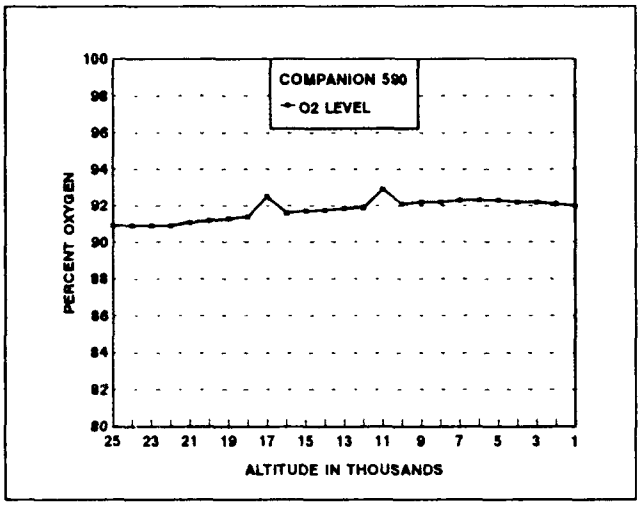
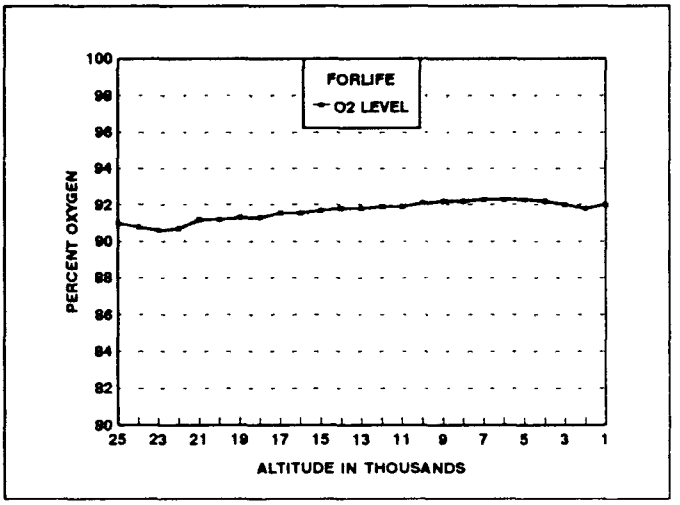
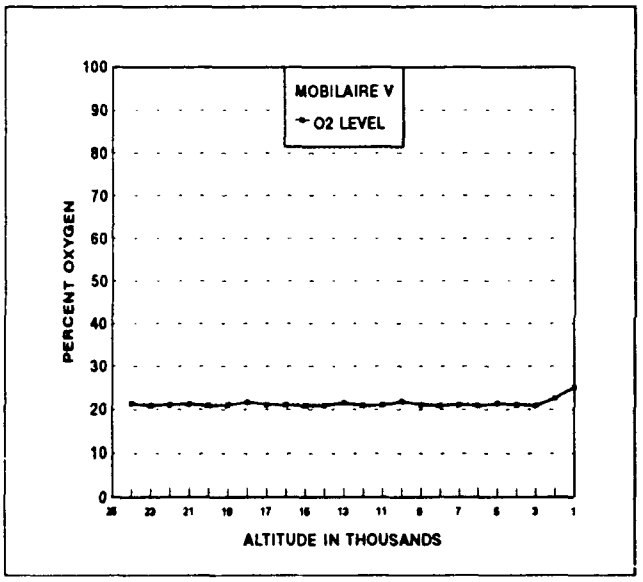
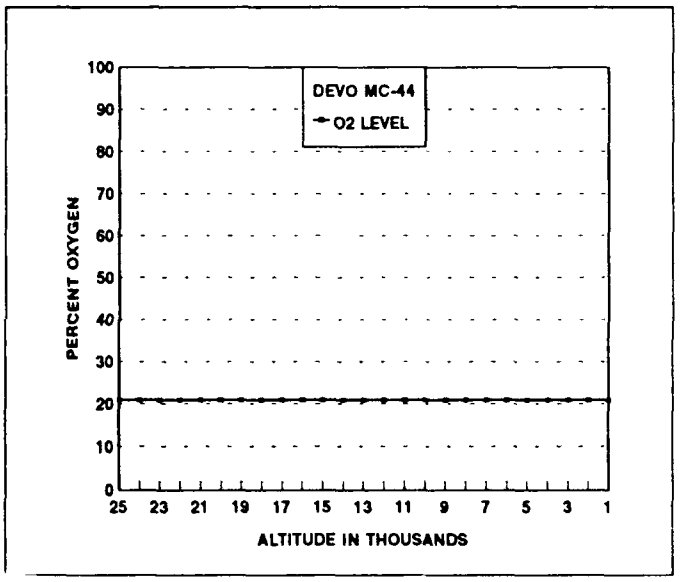



Figure 3. MSOC Tests From 25K ASL.



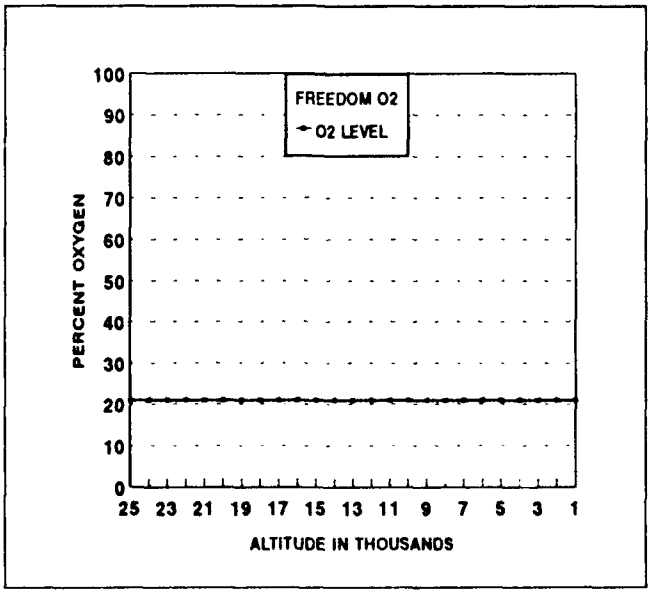
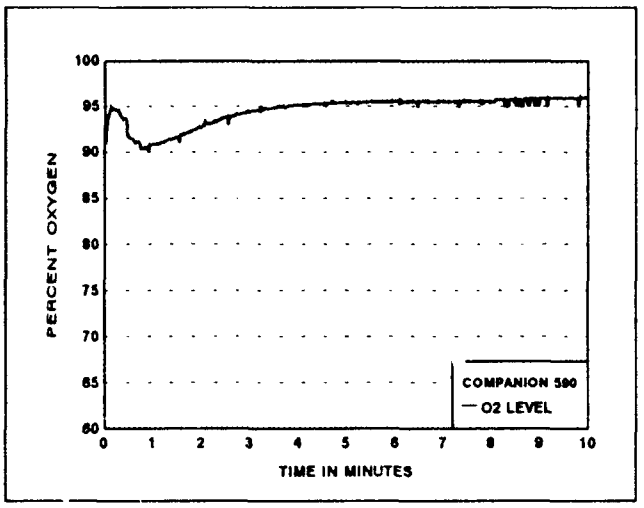
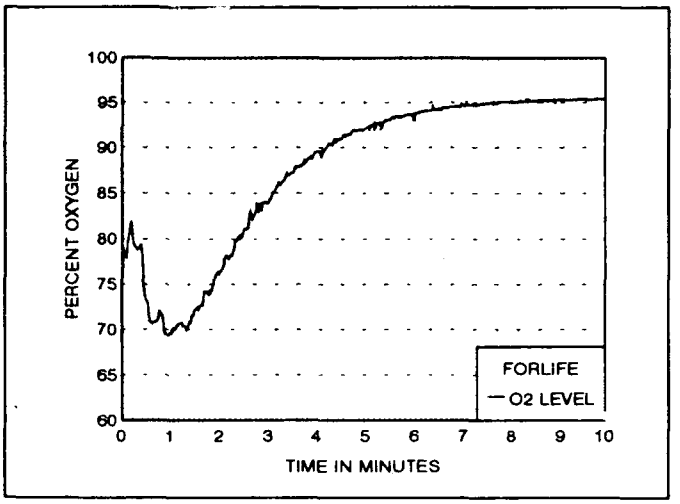
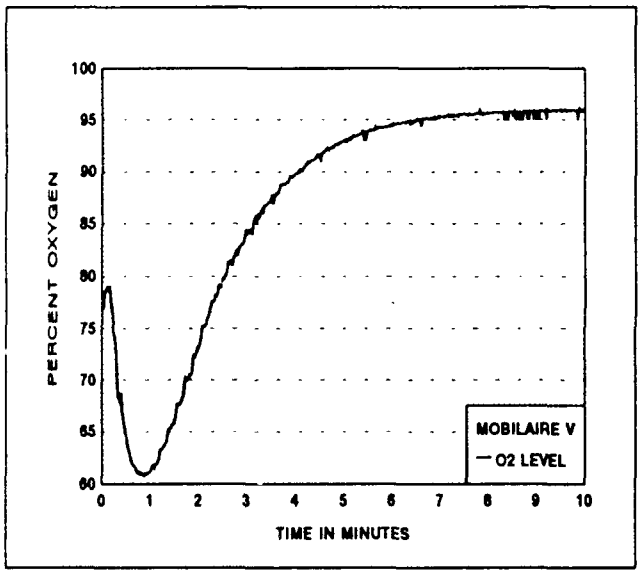
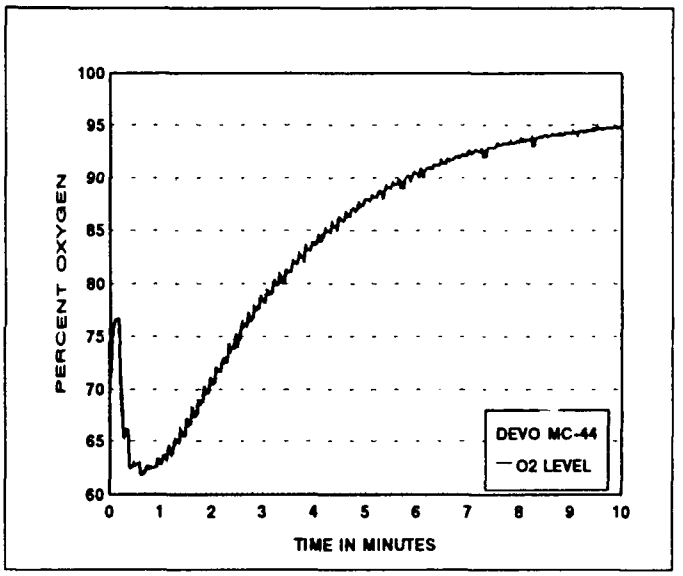



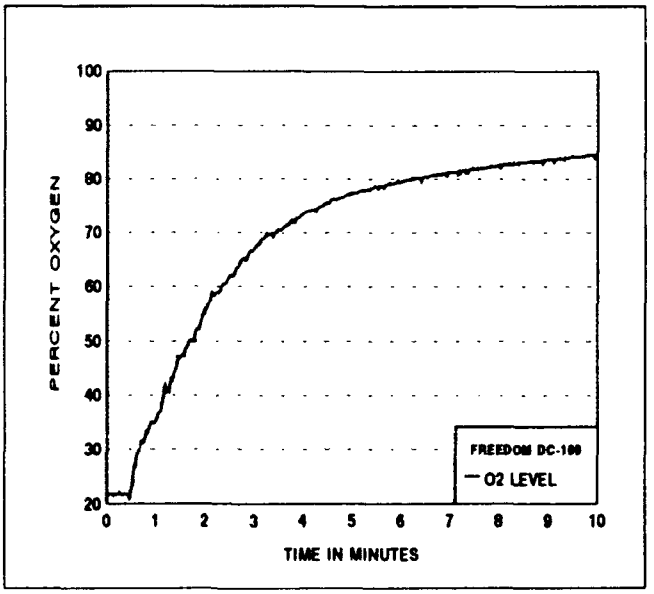
Figure 4. MSOC Tests At 8K Ft. ASL.



The DC-powered Freedom O2 DC-100 reached maximum levels after 9.5 minutes. However, the maximum oxygen level for this unit was again below 90% and the oxygen concentration rise-time curve was particularly flat. Figure 4 displays the oxygen concentration curves attained at 8,000 feet ASL.

## DISCUSSION

The results from this study indicate that Molecular Sieve Oxygen Concentrators have the potential to provide supplemental oxygen for the medically impaired air traveler. Of the units tested, the Companion 590 and the Forlife, exhibited the reliability required to assure adequate functioning in an aircraft. This finding is especially true in an unexpected decompression situation.

The biggest concern related to these 2 units is whether or not the oxygen flow at high altitudes remains adequate. The design of these MSOC units incorporates an oxygen pressure regulator that is referenced to the ambient atmosphere, which, of course, decreases in density and pressure as altitude increases. However, because of the gas expansion that occurs as the pressurized oxygen is discharged from the MSOC, the reduction in atmospheric density has little effect on the volumetric measurements provided by the MSOC flowmeters. This results in an inability to measure accurately the amount of oxygen being delivered, although the number of oxygen molecules represented by the 2 L/min flow-rate indication would be far fewer than at sea level (especially in a decompression situation). A change in MSOC regulator design to reference a constant pressure source would be necessary to assure a constant outflow of oxygen at all potential MSOC operating altitudes and would thereby alleviate this problem. However, as these MSOC typically produce lower oxygen concentrations as the flow-rate increases, using a regulator that provided the necessary increase in outflow would likely create another problem related to the ability of the air compressor to maintain an adequate air supply to the sieve beds and storage tanks. Larger, more powerful air compressors are available for such a purpose; however, until this issue has been evaluated more fully, any assurance about the ability of commercially available MSOC to supply adequate medical oxygen in-flight is questionable.

Another concern is the specific AC power that MSOC typically require. The units tested were manufactured for hospital and/or home environments, where single-phase 120 volt, 60 cycle AC is the standard in the United States. Aircraft electrical systems are generally designed as 3-phase 120 volt, 400 cycle AC. Therefore, modification of MSOC power supplies would be necessary for use aboard commercial aircraft.

In conclusion, the problems associated with MSOC appear to be amenable to standard engineering solutions. MSOC should be considered for providing medical oxygen aboard commercial aircraft. If testing of redesigned MSOC is successful, this technology appears to provide a viable alternative to the use of high-pressure oxygen cylinders aboard commercial aircraft.

## REFERENCES


1. Gong H Jr. Advising pulmonary patients about air travel. J Respir Dis. 5:484-99, 1990.

2. Dillard TA, Berg BW, Rajagopal KR, Dooly JW, Mechn. Hypoxemia During Air Travel in Patients with Chronic Obstructive Pulmonary Disease. Ann Intern Med. 111: 362- 67, 1989.

3. Gong H Jr. Advising Patients with Pulmonary Diseases on Air Travel. Ann Intern Med. 111: 349-51, 1989.

4. Stork RL, Theis CF, Ikels KG, Miller RC. Human Compatibility Testing of a 2-man Molecular Sieve Oxygen Generator. USAF Report SAM-TR-78-18, 1978.

5. Miller GW, Theis CF. Performance Studies on a Molecular Sieve Concentrator (MSOC): Comparison of MG 3, 5 AMG, and 13X Molecular Sieves. SAFE Journal, Vol. 17, No. 3, 43- 51, 1987.




*U.S. GOVERNMENT PRINTING OFFICE: 1992-661-063/60002